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Experimental Investigation of a Flapping-Jet Nozzle with a Flexible Film at Exit

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Abstract

This study investigates a new type of the flapping jets 'self-excited' by a thin FEP film fixed at the leading edge axially and centrally to the jet nozzle exit. Hot-wire anemometer and flow visualization are used to measure the flapping-jet flows induced by different-length films and also the non-flapping counterpart, i.e., the free jet without any film involving. The rectangular film length (L) is varied for L/D = 0.5 ~ 2.0 at the constant width $W = D$ while the jet Reynolds number $Re \equiv U_oD/\nu$ is taken between 10,000 and 50,000; here, U_o and D are the jet-exit velocity and diameter while ν is the fluid viscosity. It is found that the effective length of a rectangular film for the flapping to occur depends upon the exit velocity. The flapping frequency f_F reduces as L is increased and rises with increasing U_o. For the present nozzle integrating with a rectangular FEP film of L/D = 0.5 ~ 2.0 and , the flapping Strouhal number St_F ranges in $0.05 \leq St_F \leq 0.23$. These Strouhal numbers are substantially lower than that (≈ 0.65) for the primary vortex shedding in the free jet, but one to two orders of magnitude higher than those from the self-exciting fluidic devices. Results also show that the flapping jet decays and spreads far more rapidly than the free jet. The decaying and spreading rates vary with L and Re.

Introduction

Robust control of jet mixing is desirable for any practical application of fluid mixing. So, the management in jet mixing has long been a research topic for the community of fluid mechanics. Particularly of note, during 1970-90s, a great number of investigations of jet excitation were performed, see, e.g., Refs. [1-11]. Examples include acoustic excitation [1] and mechanical excitation involving moving parts [2-4]. These active excitation techniques have though proved quite effective in laboratory studies but are less feasible and ineffective in practical applications due to their weight, power and maintenance requirements. For practical applications, the excitation technique needs to be simple, without mechanically moving components, and yet effective. In this context, several types of practical self-exciting nozzle were developed for the enhancement of jet mixing, such as the flip-flop jet [5-6], the precessing jet [7-8], oscillating jet [9-10] and the "whistler" nozzles [11]. Those mechanical devices naturally excite the jet itself into time-dependent self-oscillation. It has been recognised that such a dynamic self-excited oscillation significantly increases the large-scale mixing of the jet and so benefits for some practical processes. The self-exciting nozzles have found various industrial applications [12-13]. Also, the self-excited jet oscillation has attracted attention of fundamental researchers [14-15].

However, the above self-exciting devices commonly cause a significant loss of energy during their operation. This loss is mainly due to sudden expansion and/or contraction that the working fluid flows through. To avoid this loss, we have developed a fluid-driving-film-flapping nozzle which does not have any sudden expansion or contraction and is so of energy saving. Here a very thin and light film is centrally placed along the nozzle axis at exit and flaps aerodynamically and periodically under airflow, strongly altering the downstream flow field and enhancing the large-scale mixing. The present work is designated to investigate by experiment the flapping characteristics of a turbulent jet from the round nozzle with a thin film at exit. The main objective is twofold: i.e., (1) to characterise the flapping jet for different film lengths; and (2) to compare the flapping jet with a free jet from the same nozzle without film at exit.

Experimental Details

The flapping jet flow investigated here is generated by a novel method, i.e., a jet nozzle with a flexible film placed at the nozzle exit. The experimental facility includes a round nozzle of the exit diameter D = 40 mm, to which various films with different finite length (L) can be attached. Figure 1 shows the schematic of a smooth contraction nozzle with a film and a flapping jet, together with the coordinate system. The origin of the (x,y,z) coordinates is chosen to be at the center of the nozzle exit for both the flapping and the non-flapping jets. The choice of this coordinate system results in both the flapping and non-flapping jets having identical initial conditions. The film is made of FEP and transparent with the thickness of 50 μm. Six lengths of the film were selected for the study, which correspond to L/D = 0.5, 0.75, 1.0, 1.25, 1.5 and 2.0.

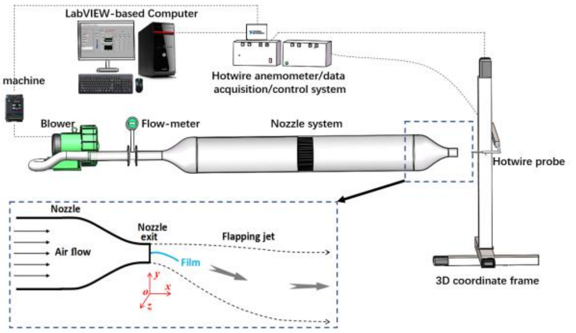

Figure 1. Experimental facilities and schematic of a smooth contraction nozzle with a sheet and a flapping jet, together with the coordinate system.

To identify the flapping-jet motion, a great number of instantaneous flow images of a smoked jet were taken by a Canon camera (EOS 5D Mark iii) equipped with the focal length 24 ~ 105 mm. The smoking was realized through a fog machine whose spray volume is 25000 ft^3/min with a nozzle diameter of 1.0 mm. The mixing between the working fluid and the seeding fog occurred in a reservoir located upstream of the stagnation chamber. The evergreen light source is class IV laser product for applications (532 nm wavelength, <10 W peak power) with an exit beam diameter of about 8 mm and the exit angle of 90 degrees. The track of the laser volume was parallel to the xy plane with the illuminated region extending for about 1000 mm along the x direction and for about 500 mm along the y direction. Here, x is the downstream distance measured from the nozzle exit and y is the lateral distance from the centreline. Of note, the film flaps predominantly in the y direction.

To compare the flapping jet with its free-jet counterpart quantitatively, the centreline velocity was measured at $x/D \leq 20$ using hot-wire anemometry. Only the streamwise velocity was taken by a single hot-wire (tungsten) probe operating with an in-house constant temperature circuit at the overheat ratio of 1.5. The hot-wire sensor, aligned perpendicular to the x-axis, is 5 µm in diameter (d_w) and approximately 1.0 mm in length (l_w) so that $l_w/d_w \approx 200$. It is normally suggested that $l_w/d_w \geq 200$ so as to enable the central portion of the wire to have a uniform temperature distribution. For the present experimental conditions, the frequency response of the hot wire and anemometer, determined by the square-wave technique, is about 100 kHz, so that the temporal response of the wire is approximately 10^{-5} seconds.

Results and Discussion

Figure 2 displays the photographs of the non-smoked mean jets from the nozzle exit with different-length films taken at Re = 0 ~ 45000. A close inspection can find that the film-flapping motion does not happen for all the lengths of L/D = 0.5 ~ 2.0 and at all Re = 10,000 ~ 45,000. Apparently, the flapping occurs for L/D = 0.5 only at Re = 45,000 or above, while it is effective for L/D = 0.75 ~ 1.25 at $Re \geq 15,000$, and for L/D = 1.75 ~ 2.0 at $Re \geq 10,000$. In other words, as the length L is increased, the film becomes easier to flap or the probability for the film to flap grows. This is expected because the film flexibility drops with shortening the film length.

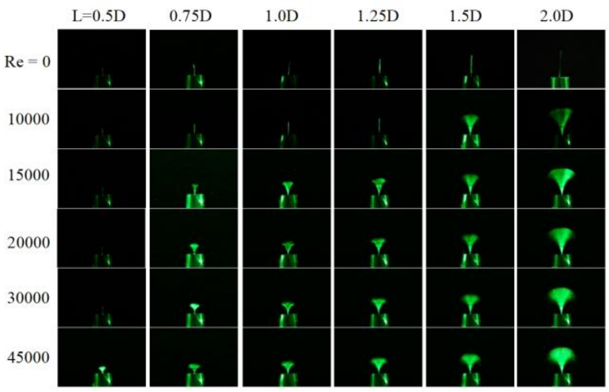

Figure 2. Mean images of the non-smoked jets from the nozzle exit with different-length films at Re = 0 ~ 45000.

Now the smoked jets are visually examined. Figure 3 shows their images taken for L = 0.75D ~ 2.0D and L = 0 (free jet) at Re = 30000. Note that the right and left images in both Figs. 3(a) and 3(b) are for the instantaneous and mean jets, respectively. Two observations can be made straightforwardly: (1) the flapping jets spread much more widely in the xy plane than does the non-flapping free jet, see Fig. 3(a); (2) the flapping jets exhibit a far less spreading rate in the xz plane than in the xy plane, despite being larger than that for the free jet. These qualitative observations suggest undoubtedly that the flapping jet induced by the film has substantially greater large-scale mixing than does the free jet.

The flapping motion is expected to be quasi-periodic. To check this, Figures 4(a) and 4(b) present the centreline power spectra (ϕ_u) of the fluctuating velocity (u), respectively, for the flapping jet and the free jet at Re = 30,000. Evidently, the primary vortex formation induced by natural instability is revealed in ϕ_u from the free jet at $x/D \leq 3$ but not from the flapping-film jet; however, the periodic flapping motion is clearly reflected in ϕ_u of the latter. The first spikes for x/D = 1.5 ~ 5 seen in Fig. 4(a) correspond to the flapping frequency (f_F). This frequency is significantly lower than the shedding frequency (f_S) of the primary vortex of the free jet that is identified by the broad peak in ϕ_u.

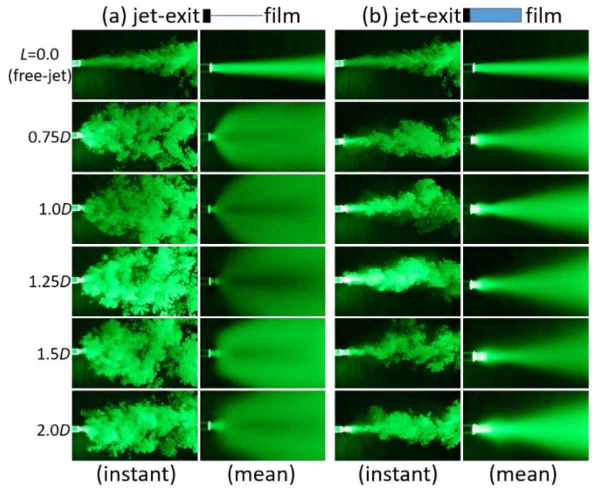

Figure 3. Images of the smoked jets, in (a) the xy plane and (b) the xz plane, from the nozzle with L = 0.75D ~ 2.0D versus the free jet (L = 0) at Re = 30000.

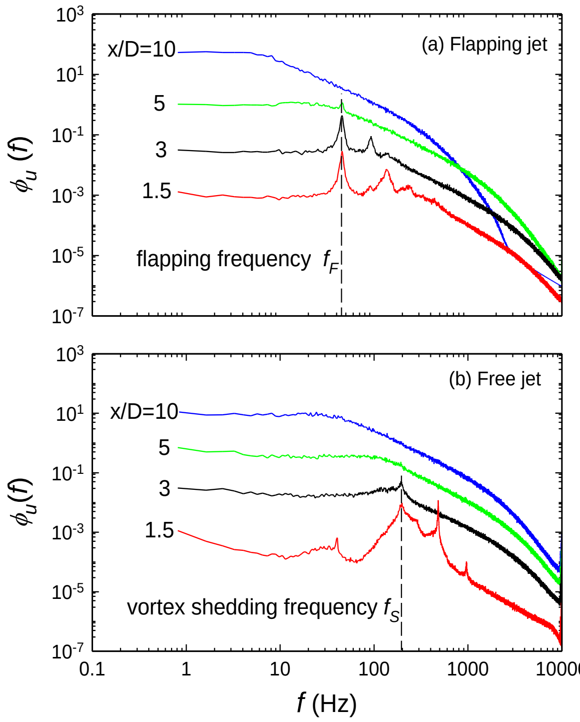

Figure 4. Power spectra of the centreline u at x/D = 1.5 ~ 10 for Re = 30,000: (a) flapping jet at L/D = 1.25; (b) free jet.

Next, the dependences of the jet-flapping frequency (f_F) on the film length (L) and Reynolds number (Re) are explored. Figure 5(a) displays the frequencies versus Re for different L. Consistent with Fig. 2, there is a lower limit of Re for any length of the film to flap effectively. And this limit rises with decreasing L. For instance, when L/D = 0.5, the limit takes between Re = 30,000 and 35,000 (cf. Figs. 2 and 5) whereas it must be smaller than 10,000 for L/D = 2.0 (cf. Fig. 2). Figure 5(a) clearly demonstrates that f_F increases with decreasing L. Also, as expected, f_F rises with the exit Re or velocity growing.

Of note, the measured relationship of f_F versus *Re* is approximately linear for $L/D \leq 1.0$, as indicated on the plot. However, this linearization has been violated for $L/D > 1.0$ perhaps due to the complex three-dimensionality of the flapping motion of the film. The flapping motion should become more three-dimensional as the film length *L* is increased. This is because the incoherence and inconsistence of local motions of the film are enhanced by enlarging *L*.

Figure 5(b) shows the dimensionless flapping frequency, i.e., the Strouhal number defined by $St_F \equiv f_F D/U_o$. Obviously, St_F grows as *L* reduces. In particular, St_F appears to keep constant for $L/D \geq 1.0$, as marked by the horizontal lines corresponding to St_F = 0.23, 0.2 and 0.17 for L/D = 0.5, 0.75 and 1.0, respectively. For $L/D \geq 1.0$, St_F varies between 0.05 and 0.15 with *Re* = 14,000 ~ 45,000. Obviously, the flapping St_F is much smaller than the Strouhal number St_p (≈ 0.5~0.7) for the primary vortex passage in the free jet estimated from f_p shown in Fig. 4(b). It is also worth noting that the present St_F ranging from 0.05 to 0.23 is much greater than those of the precessing jet (≈ 2×10^{-3}) [17] and the flapping jet (≈ 1.6×10^{-3} ~ 3.6×10^{-3}) [18]. The jet mixing characteristics is believed to depend not only upon the jet-exit *Re* but also upon the flapping St_F considerably.

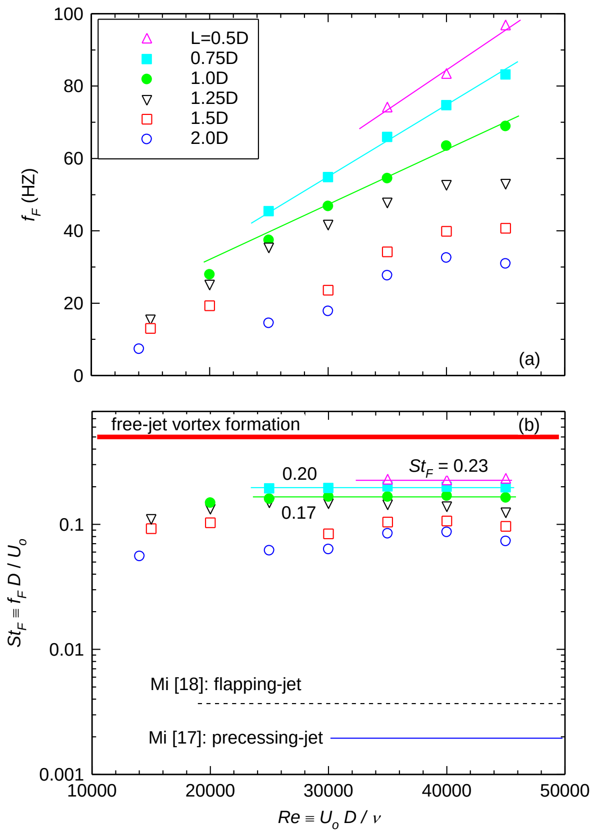

Figure 5. Jet-flapping (a) frequency f_F and (b) Strouhal number St_F versus the jet-exit Reynolds number *Re* for various film lengths.

The above belief may be verified by comparing the jet's mean-velocity and turbulence intensity distributions, various typical turbulence scales, and decay and spread rates of different St_F jets. Figure 6 shows the centreline velocity decay rate measured by U_o/U_c where U_c and U_o are the local centerline mean velocity and its exit value, respectively, for various film lengths at *Re* = 30,000. For reference, the present free-jet result and that of Mi and Nathan [16] obtained at *Re* = 15,000 are also provided on the plot. Notably, a good agreement is demonstrated between our U_o/U_c and that of Mi et al. [16], which gives a credit to the present hot-wire measurements. Indeed, as expected, the flapping jet decays generally at a much higher rate than does the free jet. This is consistent with the spreading width of the flapping jet being far greater than that of the free jet seen in Fig. 3. Moreover, Figure 6(b) illustrates that, for different *L*, the flapping-jet decay rate first rises and then drops from L/D = 1.0 as *L* is increased. This appears to reflect the effect of St_F on the mixing field of the flapping jet. as shown in Fig. 5(b).

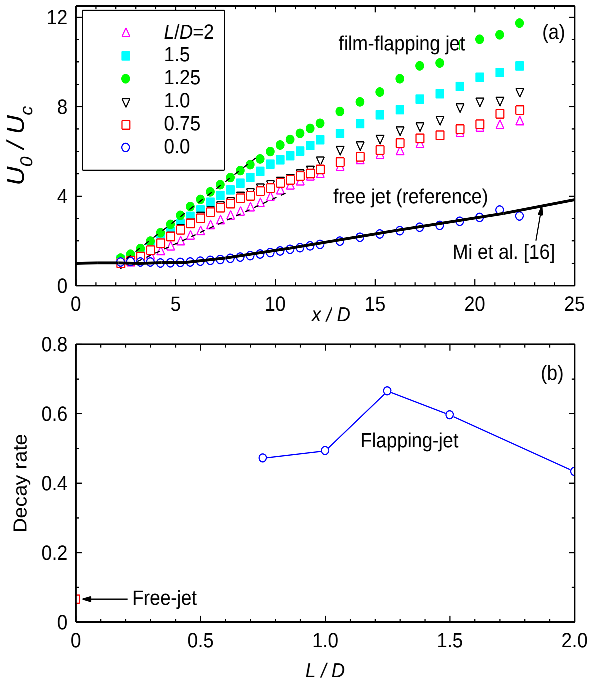

Figure 6. (a) Centreline velocity decay U_o/U_c versus x/D and (b) the decay rate versus L/D at *Re* = 30,000 for different lengths of the film.

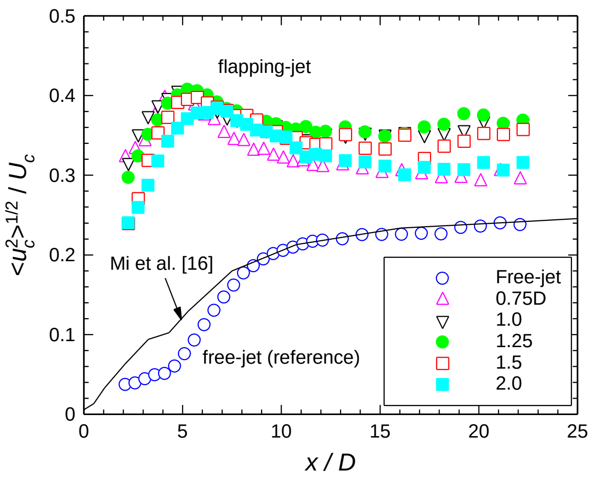

Figure 7. Turbulence intensity defined by $<u_c^2>^{1/2}/U_c$ along the jet centreline at *Re* = 30,000 for different lengths of the film.

To characterise the turbulent mixing, the turbulence intensity defined by $<u_c^2>^{1/2}/U_c$ along the jet centreline at *Re* = 30,000 is shown in Figure 7 for different lengths of the film. For comparison, the current free-jet result and that from the previous work [16] for *Re* = 15,000 are also presented on the plot. At $x/D < 8$, the present intensity is lower than that of [16] while the difference become negligible at $x/D \geq 8$. Compared with the free jet, the flapping jet exhibits a much stronger fluctuation and consequently a far higher ratio $<u_c^2>^{1/2}/U_c$ due to the large-scale flapping motion. In particular, as the flow proceeds downstream, the turbulent intensity initially grows and then turns to decrease around x/D = 5, gradually narrowing the gap from that for the free jet. Overall, the ratio $<u_c^2>^{1/2}/U_c$

is substantially greater in the flapping jet than in the free jet. Note that the turbulence intensity represents the degree at which the turbulent mixing occurs at the large scales of turbulent fluctuation. So, Figure 7 suggests that the flapping jet generally has a much greater large-scale mixing than the non-flapping jet, especially, in the near field at $x/D < 10$. In other words, the flapping film plays a significant role in enhancing the large-scale mixing of fluid in the jet flow.

Concluding Remarks

This paper discloses a new type of flapping jets that are self-excited by flutter of a flexible film with a leading edge fixed axially and centrally at a round nozzle exit. The present work has well demonstrated that there is a lower limit of length of any film below which the film cannot flap at any value of the jet-exit velocity (U_o). The flapping frequency (f_F) reduces with increasing the film length (L) and rises approximately linearly with increasing U_o for $L/D \leq 1.0$. However, the linearization cannot maintain when $L/D > 1.0$ due mainly to the incoherence of local three-dimensional motions of a sufficiently long film. The flapping Strouhal number St_F for the present round nozzle ranges in $0.05 \leq St_F \leq 0.23$. These Strouhal numbers are substantially lower than that ($\approx 0.5\sim0.7$) for the primary vortex passage in the free jet but one to two orders of magnitude higher than those of the precessing ($St_P \approx 2\times10^{-3}$) and flapping jets ($St_F \approx 2.6\times10^{-3}$) from the self-exciting fluidic devices [17,18]. Mi & Nathan [18] revealed that the jet mixing rates increase as St_F increases. Accordingly, the present flapping jet is expected to have a mixing capacity that is substantially higher than that from the fluidic nozzle.

The present work has also investigated the mixing characteristics of the flapping and non-flapping free jets. Compared with the free jet, the flapping jet decays and spreads far more rapidly and exhibits considerably stronger turbulence intensity. This agrees well with the results from the fluidic nozzle [18]. It is hence suggested that the flapping film can enhance the large-scale mixing of fluid in the jet flow. Also, Mi & Nathan [18] found that the flapping motion from the fluidic nozzle results in poor fine-scale mixing of the jet. This is however highly unlikely to apply for the film-flapping jet whose St_F is much higher. It is presently postulated that the flapping Strouhal number should impact significantly on the turbulent mixing over both small and large scales. The present authors would investigate this issue in near future.

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